Evaluation of a Microwave Blade Tip Clearance Sensor for Propulsion Health Monitoring

Mark R. Woike
NASA Glenn Research Center
Outline

- Introduction
- Motivation
  - Aviation safety
  - Engine efficiency
- Experimental Approach
- Sensor Description
- Evaluation Testing
  - Calibration Rig
  - Large Axial Vane Fan
  - NASA Turbofan
  - Calibration & Spin Rig Tests
- Planned Vehicle Integrated Propulsion Tests
- Conclusion
Introduction

- Microwave Blade Tip Clearance Sensors
  - In-situ structural health monitoring for gas turbine engines
    - Blade tip clearance to monitor growth & wear
    - Blade Tip Timing to monitor deflection & vibration
  - Active closed loop clearance control
    - Closed loop control on turbine tip clearances

- Targeting use in the High Pressure Turbine (HPT) and High Pressure Compressor (HPC) sections
  - Survivability and operation in the high temperature environment has been a major issue
  - Microwave sensor technology has the potential to operate in this high temperature environment and fulfill this in-situ health measurement need

- Summarize previous efforts in evaluating this technology
- Discuss future plans to evaluate technology on an engine ground test
Motivation – Aviation Safety

- Enhance & improve aviation safety
- NASA Aviation Safety Program (AvSP), Vehicle Safety Systems Technology Project (VSST)
  - Develop new instrumentation and techniques
  - Detect pre-cursors to events in order to take action and prevent failure

Turbine Disk Failure – June 2, 2006

Crack Detection Experiments in GRC Rotordynamics Lab

Crack Detection Experiment Results
Motivation – Aviation Safety

- FAA Report AR-08/24 “Engine Damage Related Propulsion System Malfunctions”
- Damage in the HPT and HPC sections
  - ~32% of damage events that caused engine removal for unscheduled maintenance
  - ~12% of “in flight shut down” events

Motivation – Engine Efficiency

• **Secondary goal (or primary depending on point of view!)**
  – Improve overall engine efficiency
  – Was being pursued under the NASA Fundamental Aero Program’s, Supersonic Cruise Efficiency Project

• **Active Closed Loop Clearance Control in the HPT**
  – It is estimated for every ~25um (~0.001)” decrease
    – SFC decreases ~0.1%
    – EGT decreases ~2 deg. F
  – Fuel savings
  – Reduced emissions
  – Extended service life

• **Sensor “buys” its way onto the airplane for Structural Health Monitoring**

---

Microwave tip clearance sensors and measurement developed by Radatec, Inc (now Meggitt) through the NASA Small Business Innovation Research (SBIR) Program and other commercial contracts

- Phase III SBIR commercialization contract 2006-2007
- First generation (5.8GHZ) production probes delivered in 2008
- Second generation (24GHZ) probes delivered in 2009

The use of microwave sensors for making tip clearance and tip deflection measurements is an emerging technology

- Techniques on their use and calibration need to be developed
- The sensor’s overall accuracy and ability to make clearance measurements need to be evaluated

Several evaluation experiments were accomplished from 2006 to now as a means of building toward primary goal of using these sensors on an actual engine
Sensor Description

- Probe is both a transmitting and receiving antenna
- The sensor sends a continuous microwave signal towards a target and measures the reflected signal
- The motion of the blade phase modulates the reflected signal
- The phase difference of the reflected signal is directly proportional to the distance between the sensor and the target

Microwave blade tip clearance sensor performance goals (aero engine applications):

<table>
<thead>
<tr>
<th>Measurement Range:</th>
<th>Accuracy:</th>
<th>Temperature:</th>
<th>Response:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to ~6 mm (~0.250 inches)</td>
<td><del>0.025 mm (</del> 0.001 inch)</td>
<td>~900ºC (~1600ºF)</td>
<td>&gt; 1 MHZ (5 MHZ typical, in theory up to 25 MHZ possible)</td>
</tr>
</tbody>
</table>
Sensor Description

• Microwave Blade Tip Clearance Probe
  – First generation probes (5.8 GHZ)
    • For “large” rotating machinery
    • Measurement range ~25mm (~1”)
  – Second generation probes (24 GHZ)
    • For aero engine size hardware and clearances
    • Measurement range ~6mm (~1/4”)

• Sensor Electronics
  – Contains the microwave generator and detector
  – Data acquisition & display computer
  – Located off board of test article or engine
  – Connected to sensors via co-axial cable
Calibration Experiment (FY08)

- **Objectives:**
  - To develop calibration techniques
  - To evaluate 5.8GHZ probe’s accuracy
    - Specific to the blade geometry
    - Average measurement of the geometry that is within the spot size caste on the blade
    - Need to map this “average” reading to the actual minimum clearance

- **Calibrated the microwave sensors against two geometries**
  - Over a range from 1 mm to 13 mm (.04” to .51”)
  - “Thin” compressor blade (~6 mm thick)
  - “Thick” simulated fan blade (~26mm thick)

- **Outcome / Results:**
  - Developed techniques and infrastructure required for calibration
  - Observed worst case error of $\pm 0.17mm$ ($\pm 0.007"$) during this initial experiment (on thin blade)
  - Reduced to $\pm 0.05mm$ ($\pm 0.002"$) in subsequent calibration experiments for use on NASA Turbofan
• Same sensor calibrated against two different geometries
Axial Vane Fan Experiment (FY08)

• Objectives:
  – Use the microwave sensor to make clearance measurements on actual rotating machinery
  – Evaluate how well the calibrations accomplished in the laboratory transfer into an actual use in the field

• Axial Van Fan
  – 1.8 M Diameter, operates at 1200 RPM
  – 16 Blades, ~26 mm thick (~1”) ,~362 mm (~14”) long, ~267 (~10.5”) mm chord length
  – One 5.8GHZ probe installed

• Outcome / Results:
  – NASA’s first use of these sensors on actual rotating machinery
  – Measured clearances were consistent with known operation of fan
  – Calibrations done in the lab against a simulated geometry appeared to transfer well into actual use in the field
  – *Qualitative test to gain experience with sensors*
NASA Turbofan Experiment (FY08/FY09)

• Objectives:
  – Demonstrate the microwave sensors ability to acquire blade tip clearance measurements on an aero engine size test article and blades

• NASA Turbofan:
  – Subscale turbofan propulsion simulator
  – 2 probes (5.8GHZ) installed, 90º apart
  – 18 Composite Blades
    – Blade tips were coated with nickel to allow measurement by microwave probes

• Outcome / Results:
  – Acquired tip clearance data for several test runs of the turbofan
  – The change in tip clearances measured during fan operation was in-line with previous data acquired with capacitive probes on earlier test entries
  – Demonstrated the sensor’s ability to make measurements on “aero” engine size hardware

Change in Clearance
Probe #1 Δ = 0.22 mm (~.009")
Probe #2 Δ = 0.06 mm (~.002")
Results - NASA Turbofan Experiment (FY08/FY09)

Polar Plot, Clearance vs Speed
Blade Tip Clearances in mm, Probe #1, 90 Degree Position
Run #7 9-25-2008

Average $\Delta = \sim 0.22$ mm ($\sim 0.009''$)
Spin Rig Tests (FY10-FY12)

- **Objectives:**
  - Evaluate second generation (24 GHZ) sensor’s ability to make *low range clearance measurements and deflection measurements*.
  - Evaluate their use in sensor based fault & crack detection schemes that are being developed to monitor rotor structural health.

- **Tested on several engine like disks on GRC’s Calibration Rig and the High Precision Spin Rig:**
  - Disk with blades pre-bent at specified angles for tip deflection evaluation.
  - Several disk with notches introduced to simulate cracks.

- **Results:**
  - Operated at clearances down to 0.10mm (.004”)
    - Evaluation range: 0.10mm to 0.60mm (.004” to .024”)
  - Investigated ability to make deflection measurements.
  - Sensor successfully used to monitor blade tip clearance in several crack detection experiments accomplished in our Rotordynamics Laboratory.
Spin Rig Tests (FY10-FY12)

Sensor #1 - Run #4B, SN007
Blade Tip Deflection at 0.1mm Clearance - 9/09/09

Blade Tip Deflection (mm)
Blade Number

- 8°
- 4°
- 2°
+ 2°
+ 4°
+ 8°
Vehicle Integrated Propulsion Research (VIPR) Overview

VIPR test approach:
- A series of on-wing engine ground tests
- Technologies under evaluation include advanced EHM sensors and algorithms
- Includes “nominal” and “faulted” engine operating scenarios

Partnerships:
- Sharing of costs, results and benefits
- VIPR partners include NASA, other government agencies and industry partners.

VIPR Test Schedule
- VIPR I (Dec. 2011)
- VIPR II (2013)
- VIPR III (TBD)

Testing is a necessary and challenging component of Engine Health Management (EHM) technology development.
VIPR I Test Overview

- VIPR I test was conducted in December 2011 at NASA Dryden / Edwards Air Force Base

- Test vehicle:
  - Boeing C-17 Globemaster III
  - Equipped with Pratt & Whitney F117 turbofan engines

- VIPR 1 EHM ground tests included:
  - A series of nominal and faulted engine test cases
  - Data collected over a range of power settings including quasi-steady-state and transient operating conditions
Results & Future Plans

• VIPR 1 (2011) - Microwave blade timing / tip clearance sensor
  – Not installed on engine, close as possible for EMI/EMC checkout
  – Successfully passed electro-magnetic interference (EMI) / electro-magnetic compatibility (EMC) checkout.
  – Cleared for actual on-engine use for future VIPR tests at DFRC.

  – Install microwave blade tip clearance sensors on engine in HPT section.
    – Goal of evaluating for EHM and closed loop clearance control
  – Other Advanced sensors will be installed.
  – Evaluate additional EHM sensors and algorithms under nominal and faulted engine operating scenarios
  – Initial steps towards EHM sensor fusion with advanced sensor suite.
  – Run engine to end of life.
Conclusion

• Testing to date has shown that microwave tip clearance sensor technology has proven successful in acquiring blade tip clearance measurements on rotating machinery and other “aero engine” like hardware
  – Demonstrated the techniques and infrastructure required for probe calibration
  – Used 5.8 GHZ sensors to make measurements on an Axial Vane Fan and a NASA Turbofan
  – Used 24GHZ sensors to make measurements on smaller aero engine like hardware in various test rigs

• Demonstrate in an actual turbine engine environment
  – Full scale test with a suite of EHM sensors being targeted for 2013-2014